Thermal Infrared Signatures and Heat Fluxes of Sea Foam

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ABSTRACT
The goal of this research is to quantitatively characterize the temperature change of natural sea foam in the wake of breaking surface waves as observed with thermal imaging. Measurements in a set of laboratory experiments were carried out to verify or refute the supposition that enhanced evaporative-cooling is responsible for this phenomenon. A control volume technique was successfully used to estimate the heat flux from foam and foam free surfaces in a laboratory wind tunnel. The results show that foam enhances the heat flux from seawater by a factor of 3-5. The surface thermal signature of the sea foam observed using long- and mid-wave thermal cameras, reveals an unexpected mottled texture. We infer this is due to the cooled surface fluid draining from large bubbles to the extent that they are thin enough to transmit IR radiation from warmer bulk water and foam below. A parametric bulk flux method for the heat flux due to foam and analysis of the remote sensing signature are key results of this project.

Keywords: infrared remote sensing, sea foam, heat flux, breaking waves

LONG-TERM GOALS
Goals of this project are to understand and provide missing information on the thermal infrared (IR) signature of sea surface features including wave breaking and sea foam to improve modeling and prediction efforts.

OBJECTIVES
The objective is to replicate conditions of rapidly cooling foam in the laboratory and quantify the thermal signature and heat flux due to residual sea foam. Our goals are to produce a parameterized model of foam cooling based on easily measured quantities (e.g. wind speed, air and water temperature, humidity) and determine the effect on remotely sensed thermal features.

APPROACH
To address the objectives, the technical approach will be to perform controlled environment experiments in a laboratory setting. Laboratory measurements focus on examining the surface cooling foam signature from FTIR and IR imagers for a range of typical air-water temperature differences and wind speeds in a laboratory wind tunnel. Latent and sensible heat flux mechanisms and foam properties will be examined in detail.

Air-water heat flux estimates were made based on air measurements of temperature and humidity. As is shown below, this method allows for explicit separation of the latent heat transfer from the total heat flux.

The wind tunnel is considered to be a control volume, thus heat loss from the surface foam or water can be estimated through the net balance between upwind and downwind fluxes of heat and water vapor,

$$Q_w = Q_d - Q_u + Q_L + Q_R \tag{1}$$

where the net heat flux, Q_w, from the foam into the volume of air bounded by the tunnel walls and the foam-air interface is difference of the heat flux into, Q_u, and out of the tunnel, Q_d, combined with the net latent, Q_L, and radiative heat fluxes, Q_R,

$$Q_L = L\rho_a \iint_{dA} (q_d - q_u) U_d \, dA \tag{2}$$

$$Q_d - Q_u = \underbrace{c_{pa}\rho_a \left(\iint_{dA} (1-q_d) T_d U_d \, dA - \iint_{dA} (1-q_u) T_u U_u \, dA \right)}_{dry\ air}$$

$$+ \underbrace{c_{pw}\rho_a \left(\iint_{dA} q_d T_d U_d \, dA - \iint_{dA} q_u T_u U_u \, dA \right)}_{water\ vapor} \tag{3}$$

where c_{pa} is the heat capacity of air, ρ_a is the air density, T is measured air temperature, U is the wind velocity, q is mass water vapor per the total air mass, and A is the cross-section of humid air flow. A is taken as the cross-sectional area of the boundary layer over the tank surface. Measurements upwind of the foam surface and downwind of the foam surface are denoted by u and d subscripts respectively, and q and ρ_a were determined though standard relationships.

Calorimetric method

A second method to estimate total heat flux is used as a check on the primary control volume estimates. This calorimetric method is based on the total system (test tank) heat loss during an experiment run and is the primary methodology used by *Katsaros et al*. [1977] and *Jeong et al*. [2012]. The calculated calorimetric total heat flux, Q_{cal}, is

$$Q_{cal} = -c_{pw}\rho_w \frac{V}{A}\left(\frac{\partial T_w}{\partial t} - \frac{\partial T_{tank}}{\partial t}\right) \tag{4}$$

where ρ_w is the water density, V is the water volume, T_w is a representative water temperature, and $\partial T_{tank}/\partial t$ is the heat flux from the tank water to the tank walls, in situ instruments, and eventually to the air, measured over time, t. An estimate of the tank heat loss was made by bringing the tank to temperature, covering the open tank with a tight fitting lid of foam, and measuring the temperature drop over several hours. An important difference in the implementation of the calorimetric method in this study as compared with *Katsaros et al*. [1977] and *Jeong et al*. [2012] is that we do not mechanically mix the water in the tank while the measurements were taking place due to the degradation it would have on the foam layer. Implications of this are addressed in the discussion.

Laboratory Measurements

Laboratory experiments were performed in an existing facility used to study wind influence on air-sea gas transfer [*Asher and Litchendorf*, 2009]. The system is comprised of a test tank 0.5m x 0.5m in cross section and 1m deep imbedded into the center of the test section of a wind tunnel to allow simultaneous air and water measurements, while carefully regulating air flow and water conditions as shown in the schematic in Figure 1. The wind tunnel has a test chamber 0.5m x 0.5m in cross-section and 1.5m in length. The wind turbine is capable of low speed airflow (0 - 5m/s), though much faster speeds are possible. Airflow through the test section is drawn from the room housing the wind tunnel with temperature and humidity controlled in that space by an industrial HVAC system.

Saltwater foam was generated by a submerged diffuser in the tank using laboratory compressed air filtered for water and oil. The diffuser is made from sections of permeable tubing, similar to those used in previous laboratory experiments [*Mestayer and Lefauconni*, 1988; *Camps et al*., 2005] and field simulations of seafoam [*Rose et al*., 2002]. Temperature in the water is adjusted by a flow-through, constant temperature heat exchanger and was adjusted to vary the air-water temperature difference through the experiments. The heat loss through the tank system is mediated by two-inch rigid foam insulation on the five sides of the tank. Natural, filtered seawater was used in the tank for all tests, and sodium hypochlorite was used periodically used to control bacterial growth and contamination. Prior to any tests the surface was cleaned of dust and surfactants through suctioning and physical wiping of the surface with lint free optical paper.

A pair of infrared cameras viewed and recorded the scene through ports in the top of the test section. These include a cooled long-wave QWIP array imager (8-10 μm), a cooled InSb mid-wave imager (3-5 μm), and a point measuring Fourier Transform InfraRed (FTIR) spectrometer. The FTIR provides calibrated spectral measurements between wavelengths of 3 μm to 14 μm, however the data from this system is not analyzed here. The thermal cameras were positioned to view the foam surface from an off-nadir angle to avoid direct camera reflection. The top of the test section was constructed of aluminum coated with a radiometrically-characterized paint and insulted from the top to maintain a smoothly varying ambient temperature. The IR cameras were calibrated by sampling of a precision blackbody target (Santa Barbara Infrared model 11104). A visible band camera (Point Grey Flea 3, *resolution and fov*) provided reference images of the foam layer from outside the tank.

In-water tank measurements consisted of a vertical array of seven calibrated thermistors (Sable Systems TC-2000, type T) spaced between 0.2 cm to 7.2 cm from the air water/foam interface with the top four thermistors positioned to nominally sample in the foam layer. The thermocouples were calibrated simultaneously prior to the experiment in a NIST traceable constant temperature bath with to reduce absolute temperature error to below 0.1C. Air-side instruments included up- and down-wind temperature thermistors, a Li-Cor LI-7500A water vapor analyzer (WVA) mounted downwind of the test section to measure humidity, and a cup and vane anemometer mounted down wind of the WVA. Heat flux time series were measured at wind speeds from 0.2 m/s to approximately 3 m/s. Wind speeds were limited to prevent foam and spray from contaminating the downwind water vapor and temperature measurements. Measurements of the spray produced from the foam layer (size distribution, mass flux, etc.) were not made in this experiment.

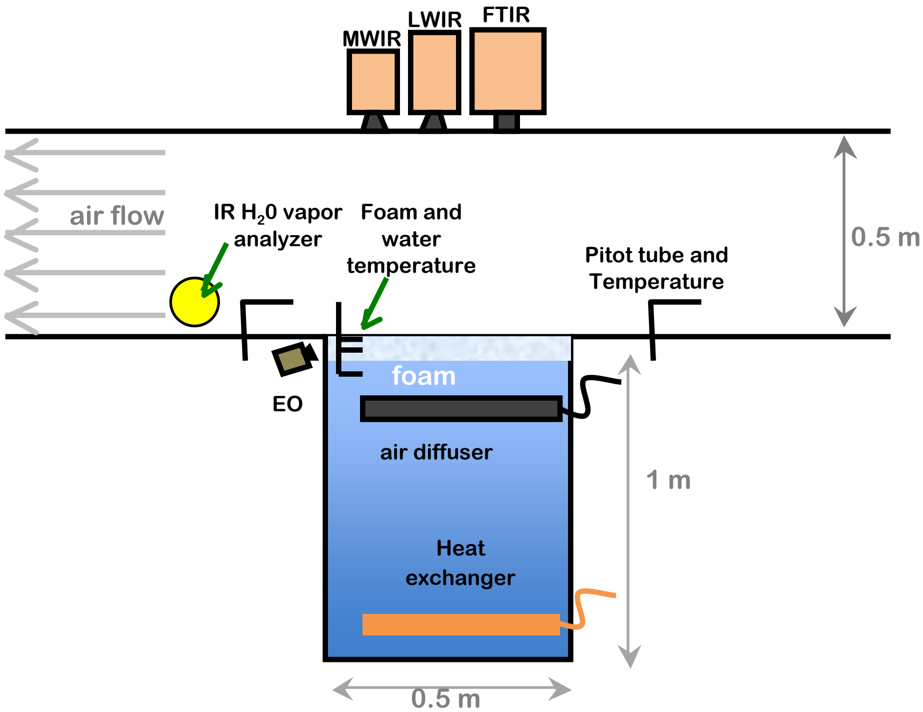

Figure 1. Schematic of the laboratory experiments performed in a wind tunnel to measure cooling sea foam. Instruments are explained in detail in the text.

WORK COMPLETED

Measurements of heat flux in the wind tunnel were completed with a focus on directly estimating heat flux based on in situ measurements and comparison between foam and foam-free surfaces. Conditions covered a range of the air-water temperature difference, relative humidity, and wind speed. Heat flux was estimated two ways, an air-side control volume method and a water-side calorimetric method. Both heat flux estimates indicate that the foamy surface has a higher heat flux than a foam free surface for similar conditions. Calibrated long-wave infrared (LWIR thermal) imagery of the foam surface shows a complex mottled temperature surface. Results below detail our findings.

RESULTS

Heat flux

Figure 2 shows the net heat flux, Q_{net}, from the foam and foam-free seawater tank surface over a range of wind speed and relative humidity conditions. Heat loss from the seawater to the atmosphere is indicated by positive fluxes. In general, measured heat fluxes increase with wind speed and decreasing relative humidity for any surface conditions. The main finding is that foam-covered surfaces have heat fluxes to the atmosphere that are three to five times the heat flux of foam-free water. Certain assumptions in the methodology will modulate the estimated heat flux values. The main factor is the assumption that the enthalpy change is confined to a constant depth (5 cm), narrow boundary layer over the tank surface, and that our fixed measurement of temperature and humidity is centered in that layer (2.5 cm height) just downstream of the tank. To verify this, we measured velocity profiles with a pitot tube over water and foam surfaces spanning our range of tested wind speeds. The profiles (not shown) demonstrate the lower boundary layer has a maximum of approximately 5-6 cm over foam and is shallower (3-4 cm) over foam-free surfaces, which is expected given the increased roughness of the foam layer. Thus the use of a fixed boundary layer depth for all conditions is not justified, but use of a thinner layer depth for the foam-free surface would result in decreased calculated heat flux and would only exacerbate the difference with a foam surface.

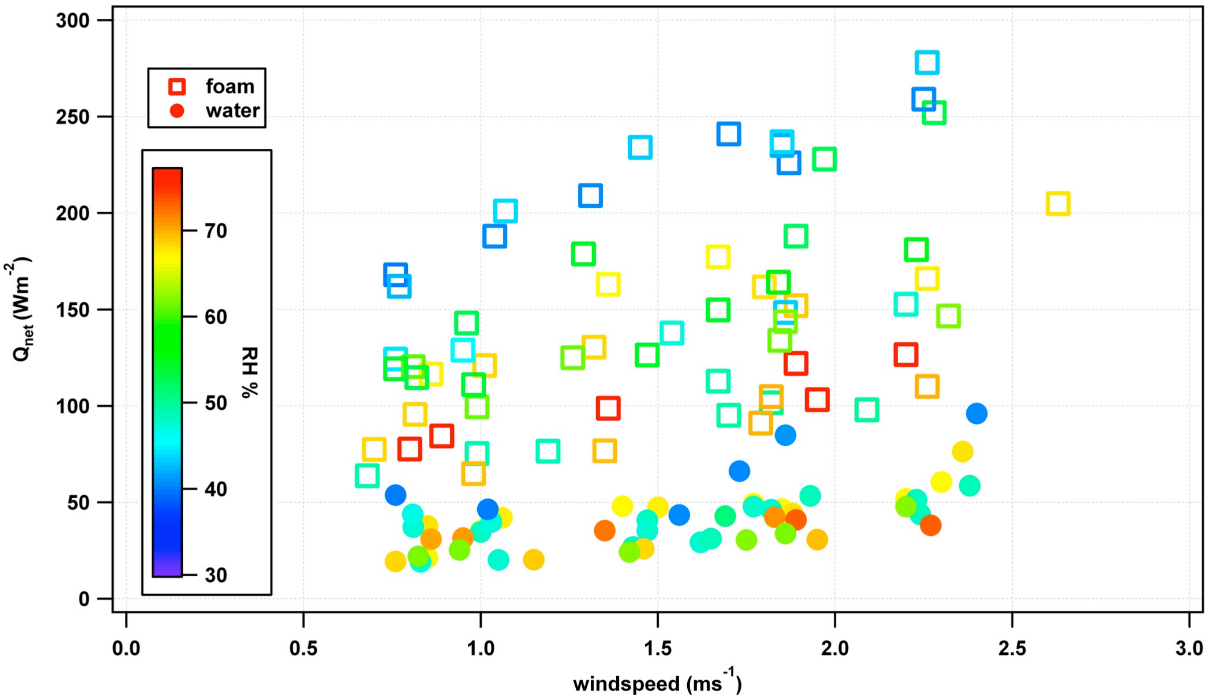

Figure 2. Summary net heat flux, Q_{net} of foam (open squares) and foam-free (water, filled circles) surface plotted versus wind speed. Symbol colors indicate the relative humidity (RH) in the test. The heat flux from a foamy surface is 3-5 higher than foam-free surface under the same conditions.

To validate the control volume heat flux measurements, we used a calorimetric method [e.g. *Jeong et al*., 2012; *Katsaros*, 1977], which uses the time rate of change of the tank water temperature to infer the heat flux, Q_{cal}, through the surface:

$$Q_{cal} = -c_p \rho \left[\frac{V}{A} \frac{dT}{dt} - \frac{dT}{dt}_b \right] \quad (5)$$

where c_p is the specific heat of seawater, ρ is the density of liquid seawater, V is the tank volume, A is the surface area of the tank exposed to the wind tunnel, and dT/dt is the rate of change of the tank temperature due to enthalpy and the subscript b is the background temperature change due to heat loss through the tank walls, measured independently. Figure 3 shows comparison of the control volume method versus the calorimetric method. Overall agreement is observed, however disagreement at higher heat flux is likely due to the fact that our water was not well mixed, thus variation due to overturning could result in noisy estimates from (5).

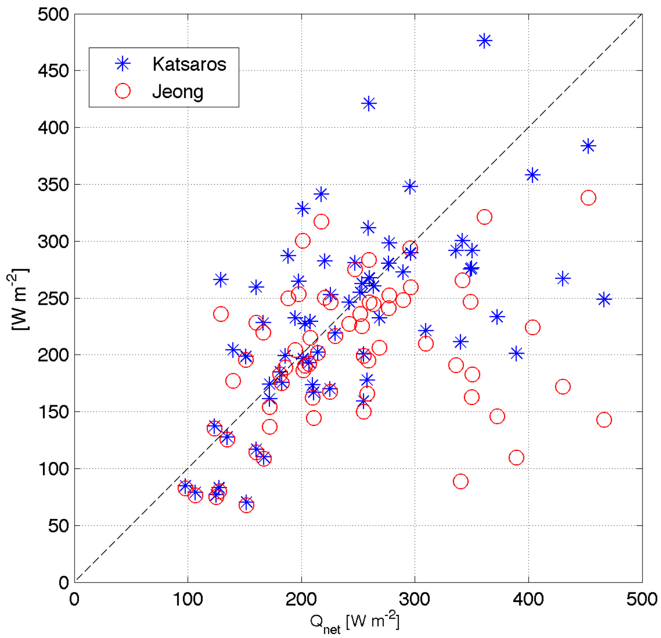

Figure 3. Calorimetric measured heat flux, Q_{cal}, versus the control volume method, Q_{net}. Agreement is generally good, but varies with methodology.

Foam Heat Flux Parameterization

A bulk method to parameterize heat flux from foam was constructed following conventional meteorological parameterizations. Ideally, the observed enthalpy flux is parameterized based on wind speed and a linear enthalpy gradient assumed from standard observations.

$$Q = \rho C_k U(k_s - k) \tag{6}$$

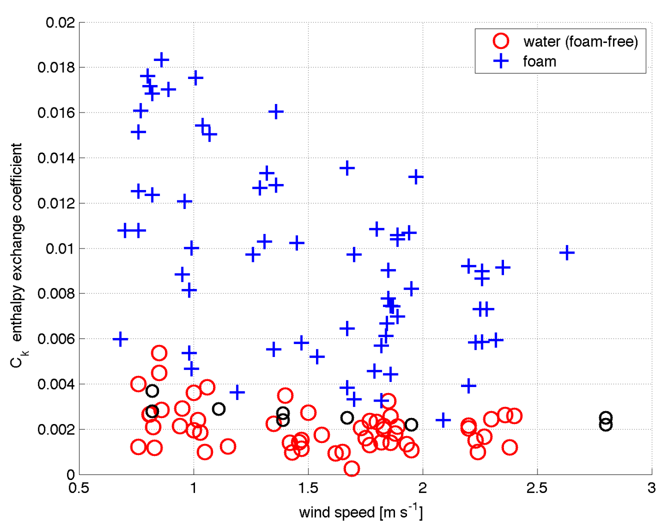

Figure 4. Enthalpy exchange coefficient calculated from our laboratory observations. Foam shows up to a ten-fold increase in the exchange over a foam-free surface.

Where C_k is an unknown enthalpy exchange coefficient that can be determined from our observations and k is the enthalpy observed at a standard height and k_s is the surface enthalpy calculated for saturated air. Figure 4 shows our resulting determination of C_k based on our measurements of enthalpy over a foam and foam-free surface. Both measurements show trends similar to observed foam-free measurements of *Jeong et al*. [2012], and our foam-free measurements agree well with theirs. Enthalpy exchange from the foam surface is dramatically increased over foam-free surface. Our test conditions did not allow for higher wind speed to be tested, though if trends hold the expectation is for C_k to increase somewhat at winds over 5 m/s.

Surface Radiometric Signature

The surface signature of the foam observed by thermal imaging reveals an unexpected temperature pattern. As shown in previous expected the mean skin temperature decreases under cooling conditions, however the detailed image shows a mottled appearance with warm and cool patches the size of the surface bubbles (Figure 5). Our interpretation is that this that the cool fluid from the prominent bubbles drains to the surrounding bubble mat and accumulates there. The bubble walls can then become thin enough (a few microns) to allow thermal radiation from the warmer bulk layer below to transmit through producing an apparent warm bubble.

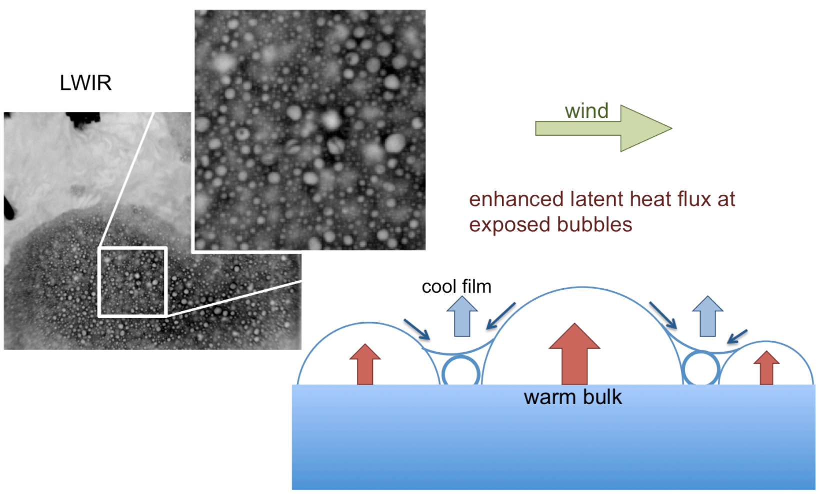

Figure 5. (left panels) The temperature pattern of cooling sea foam is characterized by relatively warm bubbles and bubble scars surrounded by cooler surface water. (lower right) The conceptual model is that prominent bubbles are cooled and wall fluid drains to the surrounding smaller bubble matrix. The thinned bubble walls are thin enough (few microns) to transmit the LWIR radiation from the warmer water and bubbles below.

IMPACT/APPLICATIONS

Results of this project will be used to improve prediction of sea surface signature and validate IR scene models of the ocean surface. Thermal radiance from breaking waves and sea foam has been difficult to predict and our laboratory measurements provide straightforward modeling paths including a bulk formula to estimate sea foam cooling. Incorporating an accurate foam cooling model will improve realistic scene generation and the signature of residual foam from waves and wakes.

RELATED PROJECTS

Directly related projects include the ONR SBIR Wake Thermocline and Thermal Scar Modeling and the recently concluded ONR project Infrared Characterization of Sea Foam. Other related projects include recently concluded River Mouth and Inlet Dynamics (RIVET) DRI and the Data

Assimilation for Remote Sensing Littoral Application (DARLA) MURI, both funded through ONR. This research may also benefit a current ONR DURIP award ('Stabilized Gimbal for Airborne Water Surface Velocity Measurements in Riverine and Littoral Environments') to measure large-scale surface temperature features in littoral regions.

REFERENCES

Asher, W. E., and Litchendorf, T. M., (2009) Visualizing near-surface co2 concentration fluctuations using laser-induced fluorescence, *Experiments in Fluids, 46*

Camps, A., Vall-llossera, M., Villarino, R., Reul, N., Chapron, B., Corbella, I., Duffo, N., Torres, F., Miranda, J. J., Sabia, R., Monerris, A., and Rodriguez, R., (2005) The emissivity of foam-covered water surface at l-band: theoretical modeling and experimental results from the frog 2003 field experiment, *IEEE Transactions on Geoscience and Remote Sensing, 43,* 5.

Jeong, D., Haus, B. K., and Donelan, M. A., (2012)Enthalpy transfer across the air-water interface in high winds including spray, *Journal of the Atmospheric Sciences, 69,* 9.

Katsaros, K. B., Liu, W. T., Businger, J. A., and Tillman, J. E., (1977) Heat thermal structure in the interfacial boundary layer measured in an open tank of water in turbulent free convection, *Journal of Fluid Mechanics, 83.*

Mestayer, P. and Lefauconni, C., (1988) Spray droplet generation, transport, and evaporation in a wind wave tunnel during the humidity exchange over the sea experiments in the simulation tunnel, *Journal of Geophysical Research, 93,* C1.

Rose, L. A., , Asher, W. E., , Reising, S. C., , Gaiser, P. W., , Germain, K. M. S., , Dowgiallo, D. J., , Horgan, K. A., , Farquharson, G., , and Knapp, E. J., (2002)Radiometric measurements of the microwave emissivity of foam, *IEEE Transactions on Geoscience and Remote Sensing, 40,* . 12

PUBLICATIONS

Branch, R., Chickadel, C., and Jessup, A. Emissivity of Seawater and Foam at Large Incidence Angles from 3-14 µm, *accepted with revision Water Resources Research*.

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14. ABSTRACT
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